Tropical Cyclone Predictability

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Grant Number: N00014-94-1-0556
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LONG-TERM GOALS

I have three closely related long-term goals. My first two goals are to estimate the so-called inherent, or intrinsic, lower limits of predictability for tropical cyclone (TC) forecast track and forecast intensity errors out to 72 hours ahead. My third goal is to develop and apply techniques to enable these inherent limits to be approached in practice and ultimately for transitioning.

OBJECTIVES

My scientific objectives are to estimate the so-called intrinsic limits of predictability of tropical cyclone mean forecast position errors in the first instance, and of tropical cyclone intensity errors in the second part of the program. I am using several techniques including Monte Carlo ensemble approaches, procedures adapted from non-linear systems analysis, and optimal combinations of forecasts. I have developed all of these schemes under ONR research grant support. The intrinsic limits of predictability of TCs exist because the equations governing the behavior of all atmospheric systems including TCs are deterministically chaotic. As such, any errors in the initial conditions and/or model formulation lead to error growth that eventually reduce the skill of the forecasts to zero. These intrinsic limits must be compared with the results that are currently being obtained in practice with state-of-the-art real-time NWP models. The size of the disparity between the inherent errors and those being attained in practice represents the gains in predictive skill that are still achievable. It is of fundamental importance to have some idea of how large the gap is between that being obtained and the ultimately achievable in order to justify the continued allocation of resources to the TC forecasting problem. The third research objective is devoted to closing this gap between the intrinsic limits and those achievable in practice. This will be achieved by improving the ingestion of *in situ*, aircraft, Aerosonde and satellite-based data, developing new 4-dimensional data assimilation schemes and improving the NWP model formulation to allow the requisite very high resolution (at least 5km) predictions to be carried out.

APPROACH

My approach is distinctive for each of the three goals. The methodology employed for the first goal has been explained fully in a series of articles (Abbey et al., 1995,1997,1999; Leslie et al., 1997, Leslie and Speer, 1998a) and involved the use of two quite distinct techniques that yield almost identical answers, thereby adding confidence to the findings. The first goal, as mentioned above, was to produce estimates of the lowest possible mean forecast track errors out to 72 hours and to determine how closely they are currently being approached in practical numerical weather prediction (NWP) models. The practical limits have been improving steadily as the sustained effort in TC track forecast continues at centers around the world. The NWP mode I have been using the model was developed at UNSW

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **Tropical Cyclone Predictability**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of New South Wales,School of Mathematics,Sydney 2052, Australia,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

and is referred to as HIRES (acronym for HIgh RESolution model). HIRES has been run in real-time for the past 5 years at UNSW and at the Sydney regional office of the Bureau of Meteorology. My approach has been to generate an ensemble of initial model states using a modified Monte Carlo technique (Leslie and Speer, 1998a and b) to the archived data sets from various operational NWP centers around the world (Australian Bureau of Meteorology, UKMO and NCEP). The initial fields are used to generate corresponding ensembles of forecasts at 12 hourly intervals out to 72 hours, after re-setting the TC positions back to their best track locations every 12 hours (Abbey et al., 1999). This approach has proven to be very robust and almost insensitive to the time interval between re-setting the TC positions to their best track locations. The alternative techniques is to use a non-linear systems approach to the archived best track data sets in the manner described by Fraedrich and Leslie (1988). Here, the spread of initially close pieces of TC trajectories is calculated over a 72 hour period for all available data sets. My second goal, which is one of the more difficult problems is be to apply the procedures that proved to be successful in achieving the first goal to TC intensity and intensity change. The task is a very long and arduous but one for which there simply are no shortcuts if believable predictability limits are to be produced. These limits will then be compared for the various TC basins and will again provide information about how close current operational models are to the limits of predictability. The third goal, which also is well underway, is to obtain much more realistic TC intensification rates and patterns than I have achieved hitherto. Before this work began, I had been producing steadily improving forecasts of TC tracks but was grossly underestimating the intensity of the storms. Other researchers had been achieving greater success using bogussed vortices and other initialization procedures but I prefer to work in the classical manner of improving data coverage and quality, data assimilation procedures, model formulation and model resolution. I achieved a major breakthrough earlier this year when I applied a four dimensional assimilation, using high spatial-temporal frequency satellite derived data of various types such as the Aerosonde, together with very high resolution modelling (5 km) and improved treatment of moist processes in the model.

WORK COMPLETED

So far I have effectively completed the first goal. The completed task calculated the difference between the mean absolute forecast track errors for tropical cyclones obtained in practice and has been compared with estimates of what could be achieved in principle. The findings were summarized below and in the 23rd Conference on Hurricanes and Tropical Meteorology, in January 1999, at which the work was presented by a co-author, Dr Robert F. Abbey Jr., of ONR (Abbey et al., 1999). My second goal of applying the same procedure to TC intensity predictability has reached approximately the halfway mark and will be presented at the 24th Conference. My third goal of greatly improving the forecasts of TC intensity and intensity change has yielded very promising results and also will be presented at the 24th Conference as well as at other meetings and has been accepted or published in several peer-reviewed journals, as discussed in the next section. An OSSE on the impact of the Aerosonde and its optimal deployment also is nearing completion and will be presented at the Conference.

RESULTS

I have now produced four main sets of results in this FY and they will be presented, in turn, below. The first set of results relates to the first goal which was to determine how close a current NWP model was to the best estimate of the limit of predictability for TCs as systems governed by a set of deterministically chaotic equations. The chaotic nature of the systems and the governing equations results from the non-linearity of the system together with the multifarious feedback processes that take

place in such complex systems. Table 1 summarizes my final set of findings from three TC basins (Atlantic, NW Pacific and Australian region) using four years of best track archived data for the period 1994-1997. The first row is the estimate of the lower limit of predictability obtained using non-linear systems analysis applied to the data and is called Inherent 1. The second row is the corresponding estimate obtained using the Monte Carlo generated ensemble NWP procedure escribed above in the APPROACH section. It is referred to as Inherent 2. The interesting feature, observed in all the previous studies is how close the estimates are from these two very different approaches to the first goal. Finally, work I carried out several years ago (Fraedrich and Leslie, 1988) was applied to the problem. It can be shown that a linear combination of several forecasts will always yield a superior forecast when averaged over a large number of forecasts. The appropriate covariances have to be calculated and this is a very time consuming effort. However, the rewards came in the form of the results in row 3 which indicated a significant reduction in TC track forecast errors when the forecasts from the UNSW, UKMO and NCEP model were combined. It is noted that this approach, referred to as Inherent 3 should be applied rigorously and simple averages might yield short term gains but have no genuine mathematical basis. It is hoped to add the NRL model NOGAPS to the list of models employed in the combination, sometime next year. The major finding is that there is still a large gap of somewhere between 35 to 50% in what is being achieved at present and what is possible. This is a very large gap in that if the 50% difference is correct, the model forecast errors of TC track position can be *halved* in the future.

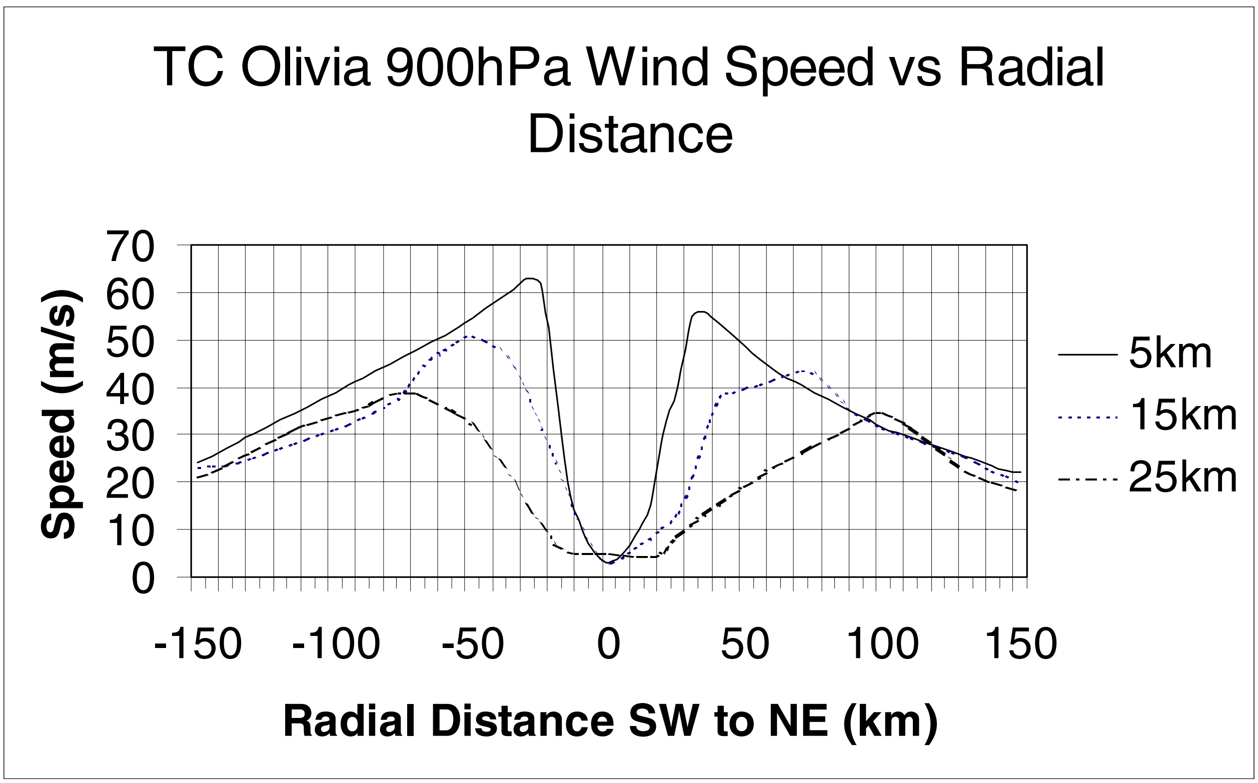
Table 1: Inherent and practical error limits (km) for the three methodologies out to 72 hours. These are to be compared with the errors currently being obtained in practice as shown on the bottom row.

	0 hr	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**
Inherent 1	**0**	**39**	**79**	**96**	**135**	**169**	**213**
Inherent 2	**37**	**53**	**85**	**102**	**141**	**177**	**224**
Inherent 3	**27**	**45**	**66**	**92**	**123**	**142**	**191**
Practical	**52**	**84**	**121**	**157**	**219**	**264**	**322**

My work on the second goal is now well underway and the first set of results is nearing completion. I have attempted to estimate the inherent errors of TC intensity and intensity change using an idealized TC in a manner similar to that in the first goal. I then compare the results with the errors obtained from operational models. This task is more difficult than the first one, owing to the fact that intensity data is of poorer quality than track data. However, careful choice of TCs can greatly improve the quality of the data. Turning to the third goal. the results I have obtained thus far have proved to be very encouraging. One of the problems I have had in common with many other TC modelers was that although the track forecasts were improved steadily (Leslie et al., 1998) the intensity of the model generated TCs was far too low. Some success has been obtained by other researchers who use bogussing techniques to estimate of the initial location, intensity, size, asymmetry and speed and direction of movement of the TC vortex. However the PI had shown in earlier work that there were major problems with the use of bogus techniques. By using a long period of numerical experiments with a range of resolutions, data assimilation techniques and model formulations and resolutions it was demonstrated (Leslie and LeMarshall, 1998, LeMarshall and Leslie, 1999) that realistic intensification of TCs could be obtained. Simply by using the standard methods of high temporal and spatial resolution data during assimilation, an effective initialization procedure, and very high resolution,

greatly improved TC forecasts of track and intensity were produced. The results of this work have been referred to as "pioneering" in a recent WMO report. One example of the ten forecasts so far carried out is shown below in Figure 1. The figure is a cross-section of the azimuthal wind for various resolutions for Hurricane Olivia. As seen clearly in the figure, forecasts that had low resolution in either the data or the model did not adequately represent the intensity and structure very well but as the resolution was increased to 5km the cross-section became very realistic. That these results have been achieved without bogussing or special initialization procedures is exciting in that it makes them the "cleanest" forecasts I am aware of using only real-time data. Figures 2 and 3 show examples of the change of central pressure with time of two very different hurricanes, Olivia and Katrina.

Figure 1: Forecasts of wind speed at 900 hPa versus radial distance from the center of TC Olivia at three different horizontal spatial resolutions and with high spatial-temporal satellite-derived winds. Note that the 5 km resolution model run resolves the radius of maximum winds very well and produces a realistic storm cross-section when compared with the much weaker winds of the 15km and 25 km resolution model forecasts.



Figures 2 and 3 below show examples of the impact of high spatial-temporal resolution data, 4DVAR data assimilation and 5 km horizontal resolution applied to two hurricanes, one during a period when it did not intensify and the other which intensified explosively to 925 hPa. In both cases the results are very encouraging, particularly Figure 3 for which the very high resolution (5km) simulations achieved deepening of almost 50 hPa compared with the observed deepening of 55 hPa. The lower resolution forecasts recorded much weaker intensifications of only 10 to 20 hPa in the 72 hour forecast period.

Figure 2: Central pressure of TC Katrina, observed and simulated by HIRES, over a 72 hour period in which the hurricane intensified only slightly, by about 7 hPa. This null case was also captured well by the model.

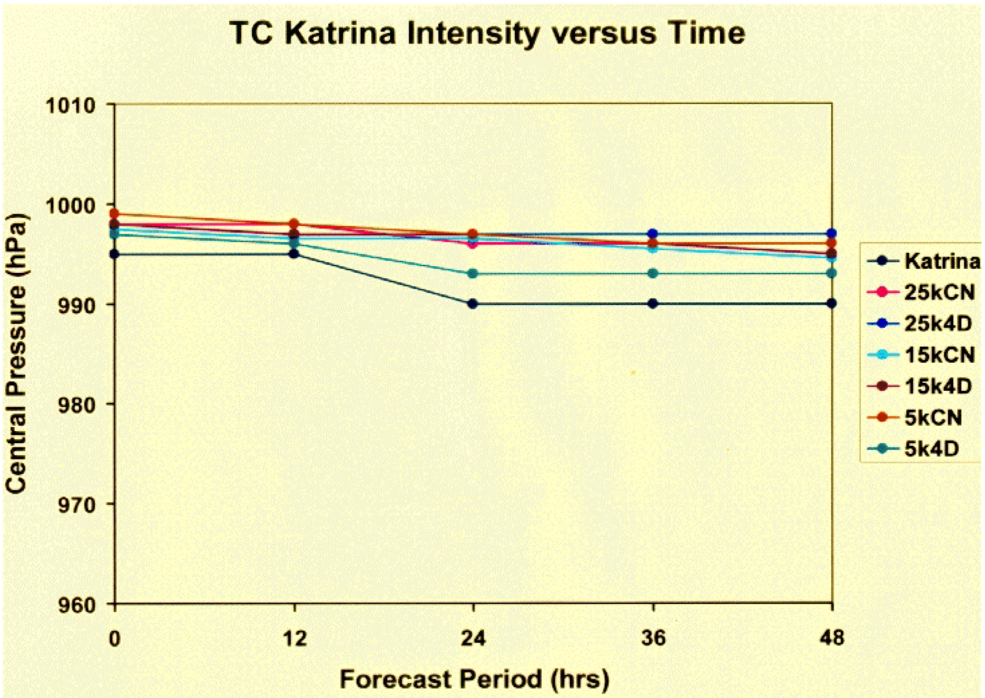
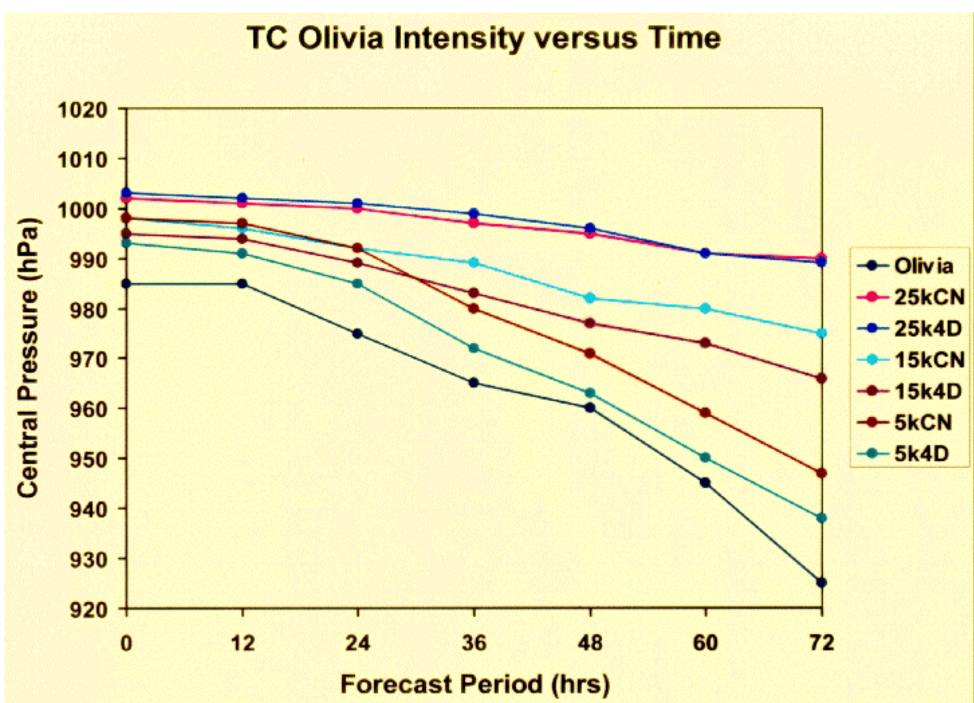


Figure 3: Central pressure, observed and simulated by the HIRES model, of TC Olivia over a 72 hr rapid intensification period using a range of model resolutions, data coverage and assimilation schemes.



IMPACT/APPLICATIONS

The proposal has produced a number of significant impact/applications. First, I have shown that TC track forecast errors are still large in that there is approximately a 50% difference between the inherent errors and the errors in practice. That is, the TC track errors still can be halved. I hope that this finding will act as a spur for continued progress in TC track forecasting. A second impact I have found is that good data, continuous assimilation and very high resolution models can achieve major reductions in forecast errors for so-called "difficult" TCs. Typically, these tropical cyclones are recurving ones. Third, I have found that realistic intensity forecasts and TC structure require resolutions of 10 km or less, preferably around 5km. My conclusions are that the prediction of TC tracks and intensities is moving within the reach of the emerging data observing systems, advanced assimilation schemes and the more sophisticated NWP models running at very high resolutions.

TRANSITIONS

I have been invited to visit NRL in Monterey sometime during 2000 to discuss possible applications of my data assimilation and modeling work to the NRL limited area model, COAMPS. Some of my work has potential for transition not only in the TC forecasting area but more generally.

RELATED PROJECTS

I have continued my close links with other ONR programs, especially that of Dr Greg Holland in an OSSE aimed at assessing the impact of the Aerosonde data on TC track and intensity prediction and with Dr JCL Chan on TC predictability using ensemble techniques. The OSSE with Dr Holland is a substantial project and will lead to some joint conference presentations and peer-reviewed journal articles.

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